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Target Diagnostic Technology Research and Development for the LLNL ICF and HED Programs

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The National Ignition Facility (NIF) is under construction at LLNL for the Department of Energy Stockpile Stewardship Program. It will be used for experiments for Inertial Confinement Fusion (ICF) Ignition, High Energy Density (HED) science, and basic science. Many issues confront experimentalists who wish to design, fabricate, and install diagnostics on the NIF. To foster this process the ICF and HED programs at LLNL have formed a diagnostic research and development group to look at issues outside the charter of facility diagnostics (core diagnostics). We will present data from instrumentation and associated technology that is being developed by this group.

A major portion of our instrumentation work is on improvements for readout systems. We have several efforts related to CCD device development. Work has been done in collaboration with the University of Arizona to backthin a large format CCD device ($36mm^2$). This work has shown good results. The device has very high quantum efficiency, low noise readout and high charge transfer efficiency. The device is being fielded in direct optical, direct x-ray and 13-15 kV electron readout applications. In addition to readout device development we have completed work on a CCD readout system. With a commercial vendor we have developed a large format, compact, Ethernet addressable CCD camera system. This system fits in shoebox size volume, is thermal electrically cooled, supports a variety of CCD devices and can be run from remote locations via TCP/IP protocol.

We are also doing work to improve streak camera systems. We have coupled our large format CCD system to an MK2 Kentech streak tube. Improvements have been made to the resolution and dynamic range of the system. Similar improvements have been made to the LLNL optical streak camera systems. We will present data from the optical and x-ray streak camera work.

In addition we will present data from single shot high-speed, high dynamic range data link work. In conjunction with the data link work we have done analysis on transient digitizer technology. We will discuss technology aimed at improvements of dynamic range for 1-6 GHz high-speed transient measurements from remote locations.

I. INTRODUCTION

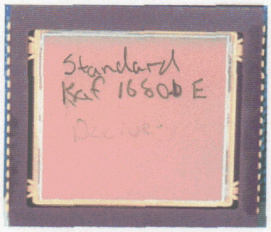
Experiments that will be conducted at the National Ignition Facility (NIF) require improvements to current instrumentation technology. This work focuses in the area of two dimensional readout systems, improvements to streak camera systems, data transmission, and transient digitizer technology. Work described will be incorporated to many integrated diagnostic systems at NIF over the coming years. Many of the system described are nearing deployment into instrumentation at the facility.

II. TWO-DIMENSIONAL READOUT SYSTEMS

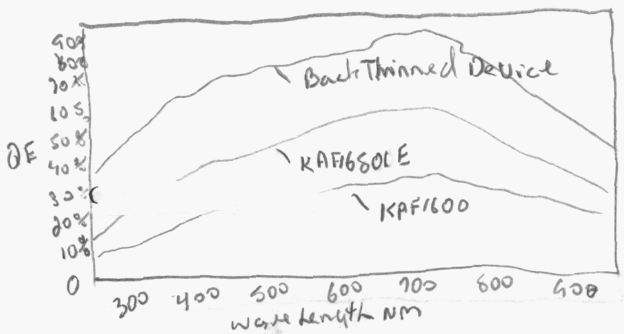
The ICF and HEDS programs at LLNL have utilized film as the media of choice for recording the output of framing camera sand streak cameras for many applications. Many of these systems are built utilizing 40mm image intensifier tubes. Typical outputs utilized 35mm rolled or 100mm by 125mm film plates of Kodak 2484 or TMAX 3200 film. Systems that have utilized CCD s have been limited. The goal of this work is to develop systems to replace film as the primary readout with enhanced performance to the integrated diagnostic systems. In addition we describe work to replace framing cameras with digital recording systems. We have broken the readout problem into two parts. The first being the sensors and second the electronics to support CCD sensor. We have done work in two areas of sensors including CCD s and CMOS sensors and have just completed work on an electronics support system.

The CCD sensor development is broken down in to three areas including optical recording, x-ray recording and electron recording. Optical recording for our applications is typically in the range of 430nm to 640nm to record the output of phosphor screens. Electron recording in the range of 13-15keV electrons for streak cameras applications. The application for x-rays is broad, but we will discuss the sensitivity of the large area device we have developed. Several criteria were used to choose a suitable device for this broad range of applications. The device had to be capable of direct one to one coupling of a typical 35^2mm output, a pixel size in the range of 15 microns in addition be readily available and reasonably priced. At the start of this development there were few devices that fit this criteria. Today there are still few selections for such devices at reasonable costs. The sensor we have based our development around is the Kodak KAF 16800 (4k x 4K 9μm pixel) 36.88^2mm family of devices.

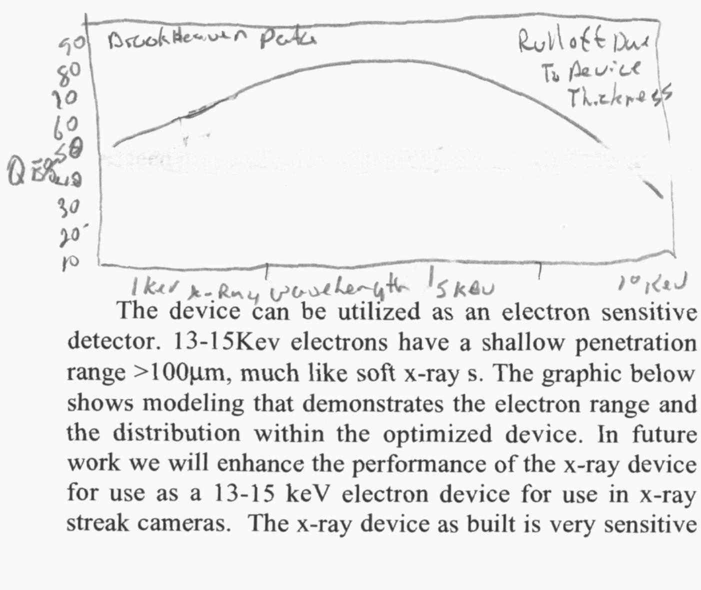
Under contract and collaboration with the University of Arizona we have backthinned devices obtained from Kodak. The devices were purchased in wafer form to allow for handling and processing. The devices were than packaged to be pin for pin compatible with standard front illuminated Kodak 16800-product family. Each application requires specific backside processing to enhance the quantum efficiency of the device for their application. We have devices that are interchangeable and are operated by a common electronics system.



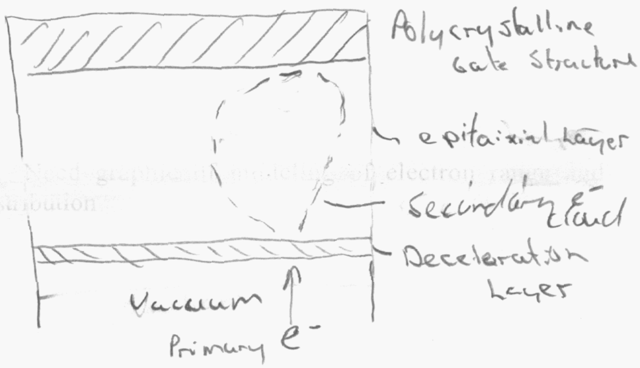
Our work related to optical wavelength enhancement of this device is to increase the open area ratio of the device and enhance coatings for fiber-optic bonding and coupling to phosphor screens. Typical front-side illuminated sensors that we have utilized have quantum efficiencies that range from 15% to 40% depending on the wavelength of operation and gate structures of the device. We have demonstrated quantum efficiencies of 85% at 640nm. The devices built to date exhibit charge transfer efficiency of 99.99998 The next step in this area of work is to bond a device to a large fiber bundle and measure the quantum efficiency of the bonded devices.



Two devices have been fabricated for use as soft x-ray detectors. The passivition of the backside surface is the critical process that allows for enhanced Qe for use as low energy x-rays. Through careful work we have reduced the oxide layer and other contaminates that are very absorbing to soft x-rays (>1keV). The graph shows our quantum efficiency of this device from 200ev to 6 keV x-rays. The high-end cutoff is due to the silicon thickness of ~15µm. We have other work that addresses a higher range of x-ray sensitivities, but won t discuss that here. We have measured read-noise from these two devices to be 3 electrons at —100 to —20 C which is has been non-typical for the Kodak KAF 16800 family of devices.



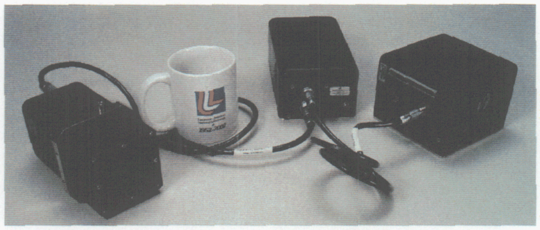
The device can be utilized as an electron sensitive detector. 13-15Kev electrons have a shallow penetration range >100µm, much like soft x-ray s. The graphic below shows modeling that demonstrates the electron range and the distribution within the optimized device. In future work we will enhance the performance of the x-ray device for use as a 13-15 keV electron device for use in x-ray streak cameras. The x-ray device as built is very sensitive for this energy range of electrons creating excessive secondary electrons in the CCD. By applying a 1000 angstrom layer of aluminum we can optimize the electron energy deposited within the field region of the CCD. Optimally we would have 3 sigma counts over manufactures published device read noise of 9 electrons or ~36 electrons per incident 13-15Kev photoelectron. The aluminum optimization will enhance the dynamic range of this device allowing for single electron measurement capability while maintaining a minimum dynamic range of 10 bits without binning the 9µm pixels or as high as 14 bits with 2 x 2 binning and 18µm pixels size. The device is limited to 14 bits as the output amplifier is specified to hold ~2.7 x 10^5 electrons. This limit is well matched to the x-ray streak camera applications. Much of this work has been demonstrated utilizing smaller format commercially backthinned devices.



Need graphic of modeling of electron range and distribution

III. MODEL SI1000 CCD CAMERA

Under contract with Spectral Instruments we have developed a compact network addressable scientific grade CCD electronics support system. The system includes the camera head with Kodak CCD, controller and power supply. In order to maximize the use of the controller an analog and digital input/output option in the camera controller permits control of both the camera head and other diagnostic functions via a single Ethernet link. The model SI1000 camera design is based on Spectral Instruments model SI800 camera. A PC104+ controller and the DC power supply have been added. The measured camera performance with 16 bit digitization has a dynamic range of 70 dB (limited by CCD device) with read noise of 7 electrons at 680 MHz readout rate. The spatial resolution as measure by Spectral Instruments is 52 lp/mm. The PC104+ controller consists of the following four boards: Spectral Instruments gigabit fiber link/camera controller board, Spectral Instruments fiber optic Ethernet board, WinSystems PPM-TX-266-ST CPU board, and the optional Diamond MM-16-AT analog/digital I/O board. The Diamond board with 16 analog inputs, 4 analog outputs and 16 digital I/O. Communication between the controller and the NIF network is by the fiber optic Ethernet and the link between the controller and camera head is also via fiber optic. This configuration should reduce electromagnetic pulse and electromagnetic interference problems.



IV. X –RAY STREAK CAMERA SYSTEM

The ICF program at Livermore has an inventory of Kentech x-ray streak cameras that were built in the 1980s and 1990s. Today, these cameras are still very functional. We have designed and implemented several improvements to the Kentech x-ray sensitive streak camera system. We are employing a modified Marconi 42-40 large area CCD to directly absorb accelerated photoelectrons emitted from the photo-cathode. The chip features full frame architecture in a 2k by 2k imaging array and 13.5 by 13.5 square microns individual pixel size ($26mm^2$). The existing AR coating is not optimized for the electron current parameters within the drift tube. We will be deploying a Kodak optimized device as previous mentioned.

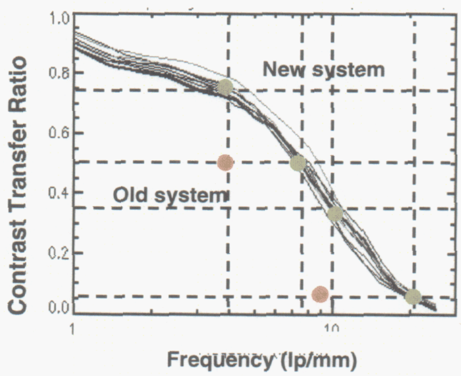
We have also done work to improve the off axis spatial resolution. These improvements have been integrated into a streak camera system originally built by Kentech Instruments Ltd. Variations of this system have been fielded routinely on the LLNL Nova and Janus lasers.

We have collected a substantial set of system performance data, which has been obtained from both bench top experiments on a DC source and dynamic measurements from laser facilities. X-ray images at various exposure times show better spatial resolution, improved signal to noise ratio and higher dynamic range compared to the previously used recording systems. Dynamic range measurements show linear performance over 12 bits and allows for single photon counting.

Based on the geometry of the drift tube we have designed and fabricated spherically curved photo-cathodes to improve the off center defocusing caused by planer tube geometry.

V. Optical Streak camera systems

The ICF program at Livermore has a large inventory of optical streak cameras that were built in the 1970s and 1980s. The cameras include microchannel plate image-intensifier tubes (IIT) that provide signal amplification and early lens-coupled CCD readouts. Today, these cameras are still very functional, but some replacement parts such as the original streak tube, CCD, and IIT are scarce and obsolete. We have made efforts to improve the performance of these cameras using today s advanced CCD readout technologies. Very sensitive, large-format CCD arrays with efficient fiber-optic input faceplates are now available for direct coupling with the streak tube. Measurements of camera performance characteristics including linearity, spatial and temporal resolution, line-spread function, contrast transfer ratio (CTR), and dynamic range have been made for several different camera configurations: CCD coupled directly to the streak tube, CCD directly coupled to the IIT, and the original configuration with a smaller CCD lens coupled to the IIT output. Spatial resolution (limiting visual) with and without the IIT is 8 and 20 lp/mm, respectively, for photo cathode current density up to 25% of the Child-Langmuir (C-L) space-charge limit. Temporal resolution (fwhm) deteriorates by about 20% when the cathode current density reaches 10% of the C-L space charge limit. Streak tube operation with large average tube current was observed by illuminating the entire slit region through a Ronchi ruling and measuring the CTR. Optimum spatial resolution is achieved when the IIT is removed. Maximum dynamic range requires a configuration where a single photoelectron from the photocathode produces a signal that is 3 to 5 times the read noise. The elimination of the IIT and the addition of the large-format CCD show great promise. Spatial resolution improves with the elimination of the MCP IIT. With implementation of earlier described large-format CCD the dynamic range performance comparable to systems fielded in past configurations.



VI. Data Links

The National Ignition Facility at Lawrence Livermore National Laboratory requires high-bandwidth and high-dynamic range data transmission from the target chamber area to diagnostic recording equipment at a distance of approximately 150 feet. We are approaching this requirement using three separate methods. We are evaluating both commercial modulated lasers / fiber-optic analog data links and attenuation and phase compensated, low-loss coaxial cable systems. We are also pursuing new concepts to provide both the data link and improve the resolution of the recording system. One such system utilizes high-speed serial optical sampling and wavelength domain demultiplexing of the samples into a parallel array of slower speed channels. Systems are evaluated on their bandwidth (3 GHz minimum, greater than 5 GHz preferred), signal loss, ability to accept high power levels, usable dynamic range (as high as possible effective number of bits is desired), and immunity to a large external electromagnetic pulse. The systems need to pass short pulse signals with high fidelity, requiring a linear phase response to an impulse. To date, we have characterized three fiber-optic systems, and tested two iterations of a compensated cable system.

In the past single event analog data links was typically below 1 GHz. Data links ≥converting the electrical signal to optical and recording the signal with a streak camera handled 1 GHz data. .
The short-term goal is at 3 GHz bandwidth analog signal link from the Dante x-ray diodes to the digitizers. The digitizers are approximately 150 feet from the diagnostic. The long-term goal is to increase the frequency to 6 GHz. The analog link can be either optical or electrical. An industry survey of optical analog links showed the majority of industrial systems are meant for remote operation of L-band satellite and cellular phone antennas with narrow band operation below 3 GHz.

Optical links were purchased from PPM and Ortel/Agere. In addition Microwave Photonic System developed a custom system. All three systems are based on directly modulate distributed feedback lasers. The commercial 2 GHz system from PPM is meant for applications in a high EMP environment with battery operation. The Ortel system consists the transmitter module 3541A-001-005-020 and the receiver module 45B-20. In figure 1 the frequency response of the PPM drops off long before the others since it is sold as a 2 GHz system. In figure two the Ortel system shows more drop than the others. This is due to higher low end cut off frequency.

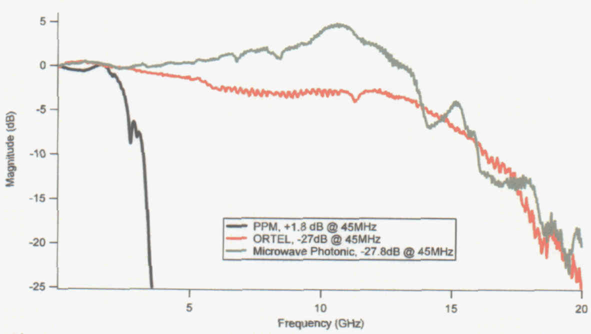


Figure 1. Frequency response of the optical links.

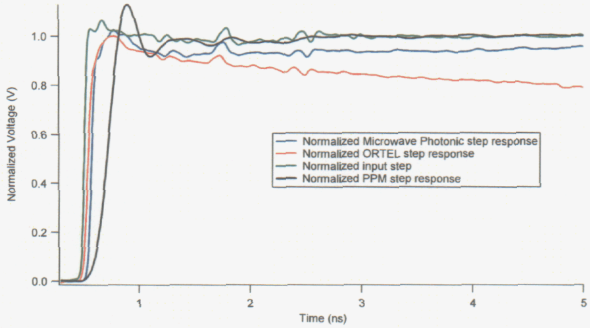


Figure 2. Step response of the three optical links

A passive, low-cost alternative to a laser-based link is an attenuation compensated low-loss coaxial cable. This approach was successfully used in the Underground Test Program for signals less than 1 GHz. While cable compensator technology has in the past only been available over limited bandwidths, there are currently vendors capable of producing compensators up to the 10-20 GHz range. For the application of high-bandwidth coaxial transmission, the main limitations for this approach are the attenuation inherent at high frequency in a long coaxial cable, the phase linearity of a passive compensator, and the upper frequency cutoff for low-loss coaxial cable as it approaches higher order mode operation.
For the initial evaluation of the compensated cable alternative, a bandwidth of 6 GHz was selected due to the cable characteristics, and the availability of compensation components. The cable compensators limit the power handling capability of the system to 100 Watts (+50 dBm) for a 5 ms pulse length. Capability of handling high power levels is a distinct advantage for the passive compensated cable system compared to the laser-based system in consideration of signal to noise issues. A 100-Watt peak signal would need to be attenuated by 40 dB to be transmitted through the Ortel system described previously.
MCE/INMET Corporation built the first generation unit. MCE/INMET builds high frequency cable compensator but with a narrow bandwidth. Figure 1 and 2 show the frequency response and step response of the cable, compensator and the combination. Figure 3 shows the phase response. The phase response can be improved by not using a corrugated cable

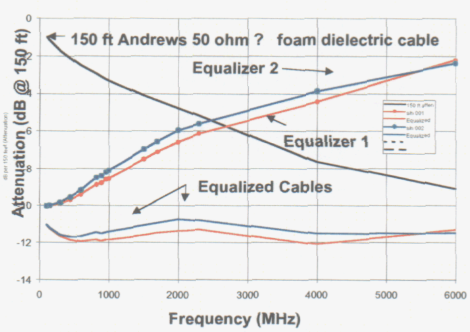


Figure 1: Frequency response of cable, compensator and combination.

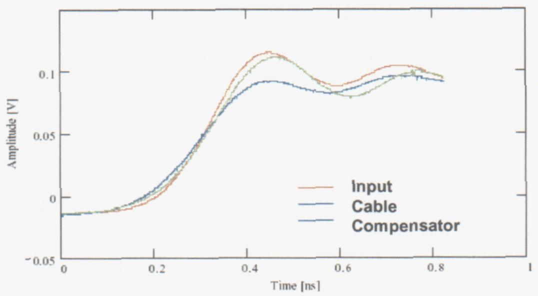
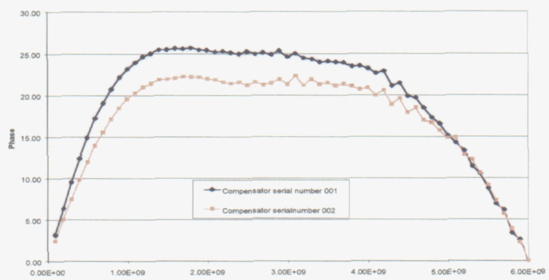


Figure 2. Step response characteristics of uncompensated



cable

Figure 3. Phase response of compensated cable

Summary of optical links

Both the fiber optic approach and cable compensation will meet the short-term goal of 3 GHz analog bandwidth. The first installation of Dante will use coax cable with frequency compensation. However, a non-corrugated cable LMR600 is replacing the LDF4 cable in order to improve phase response. MCE/INMET and Bechtel Nevada Operations are working together to extend the frequency response of the cable compensator system below 100 MHz and improve the phase response.

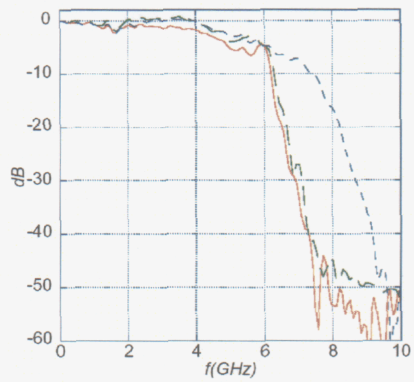
High-speed Digitizers

In the past the high-speed recording options with ≥8 bits of resolution were limited to the 7250, SCD5000 or the IN700. The 7250 was an 8 bit digitizer with 6 GHz bandwidth. An alternate technology using scan conversion to quickly store the signal and then digitize at a slower rate was used in the French IN700 and Tektronix SCD5000. The Tektronix SCD5000 was rated at 11 bits with a 4.5GHz bandwidth. Neither the IN700 or SCD5000 are still in production. The test community has lost the ability to digitize and record single event signals with ≥ 2 GHz bandwidth and ≥ 8 effective bits.

The two-part goal is the high speed digitizing of NIF optical and x-ray measurements with a high dynamic range. The initial diagnostic digitizing and recording system requires a 3 GHz bandwidth with 5 effective bits. A current approach to increase the dynamic range is to split the signal between scope channels with different sensitivities Once the signal is recorded the data is recombined and shifted in voltage to reproduce the original signal pulse.

The first system will be followed up with high performance system with 6 GHz bandwidth and 12 effective bits. A fundamental problem is the number of effective bits drops as the sampling rate increases. At giga-samples per second (GS/s) aperture jitter is the major factor limiting the number of effective bits.[1] Typical specifications state 8 bits at 20 GS but the actual effective bits are less than 6 when digitizing a 5 GHz analog signal pulse.

An evaluation was done on the three commercial oscilloscopes with a 6 GHz analog bandwidth. All three oscilloscopes use 8 bit digitizers and maximum sampling rate of 20 GS/s. Two of the oscilloscopes use digital signal processing (DSP) to enhance the perceived performance. The DSP function used to alter the waveform was a sin(x)/x However, tests with step inputs showed DSP added a pre-transition aberration that was between 3.1% to 1% while the non DSP unit had 0.5%. Figures 1 and 2 show the frequency response and step response of the three oscilloscopes. Both oscilloscopes with DSP had sharper roll off past 6 GHz but the noise



floor is similar for all three oscilloscopes.

Figure 1. Frequency response plot of the three commercial oscilloscopes

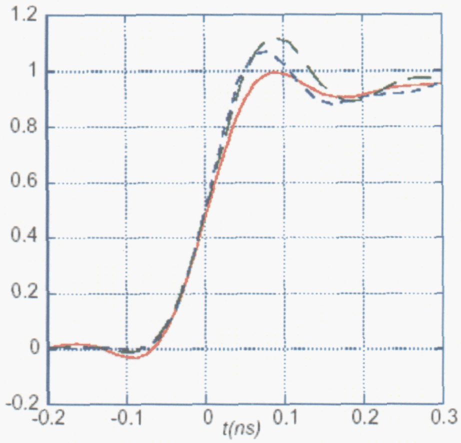


Figure 2 Step response plots of the three oscilloscopes. The step input signal had a 15ps rise time.

Additional measurements were done to etermine the effective number of bits versus frequency and amplitude of the signal. The oscilloscopes were set to 100mV/div and the

large signal was 90% full scale and the small signal was 20 full scale. At both 1 and 5 GHz the average large signal digitization was 5.4 effective bits. At 1 GHz the average small signal digitization was 5.9 effective bits and 5.8 effective bits at 5 GHz.

Summary

The ICF and HEDS programs are working to improve the data recording capabilities. We have present data from instrumentation technology that has been developed by this group. A major portion of our instrumentation work recently has been devoted to improvements to streak cameras though improved CCD systems. We have improved spatial resolution while maintaining good quantum efficiency. We have developed a large format, compact, Ethernet addressable CCD camera system that will reduce the staffing and spare parts required for the large number of cameras required for NIF. We have a field ready solution for measuring diode signals from remote locations of the NIF. Additional target diagnostic technology research and development for the LLNL ICF and HED programs are required and will continue in the future.

K.S. Budil Rev. Sci. Insturm. 67 (2), Feb 1996
Paper by Dick describing streak cameras
Kodak Image Sensor www.kodak.com/go/imagers
University of Arizona, Mike Lesser, Ph.D. Imaging Technology Laboratory; Tucson, Arizona 85721 Spectral Instruments Tucson, Arizona 85745
Kentech Instruments, Ltd., South Moreton, Didcot, Oxfordshire, OX119AG, UK
Franz is there a reference for the nova work
SPIE by Joe McDonald.
Robert H. Walden, Analog-to-digital converter survey and analysis, IEEE J. Sel. Area. Comm., Vol. 17, No. 4, pp. 539-550, April 1999.